

FIRST EVIDENCE FOR NEUTRINOLESS DOUBLE BETA DECAY

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Double beta decay is indispensable to solve the question of the neutrino mass matrix together with ν oscillation experiments. Recent analysis of the most sensitive experiment since nine years - the HEIDELBERG-MOSCOW experiment in Gran-Sasso - yields a first indication for the neutrinoless decay mode. This result is the first evidence for lepton number violation and proves the neutrino to be a Majorana particle. We give the present status of the analysis in this report. It excludes several of the neutrino mass scenarios allowed from present neutrino oscillation experiments - only degenerate scenarios and those with inverse mass hierarchy survive. This result allows neutrinos to still play an important role as dark matter in the Universe. To improve the accuracy of the present result, considerably enlarged experiments are required, such as GENIUS. A GENIUS Test Facility has been funded and will come into operation by early 2003.

1. Introduction

Double beta decay is the most sensitive probe to test lepton number conservation. Further it seems to be the only way to decide about the Dirac or Majorana nature of the neutrino. Observation of $0\nu\beta\beta$ decay would prove that the neutrino is a Majorana particle and would be another clear sign of beyond standard model physics. Recently atmospheric and solar neutrino oscillation experiments have shown that neutrinos are massive. This was the first indication of beyond standard model physics. The absolute neutrino mass scale, however, cannot be determined from oscillation experiments alone. Double beta decay is indispensable also to solve this problem.

The observable of double beta decay is the effective neutrino mass

$$\langle m \rangle = |\sum U_{ei}^2 m_i| = |m_{ee}^{(1)}| + e^{i\phi_2} |m_{ee}^{(2)}| + e^{i\phi_3} |m_{ee}^{(3)}|,$$

with U_{ei} denoting elements of the neutrino mixing matrix, m_i neutrino mass eigenstates, and ϕ_i relative Majorana CP phases. It can be written in terms

of oscillation parameters ⁵

$$|m_{ee}^{(1)}| = |U_{e1}|^2 m_1, \quad (1)$$

$$|m_{ee}^{(2)}| = |U_{e2}|^2 \sqrt{\Delta m_{21}^2 + m_1^2}, \quad (2)$$

$$|m_{ee}^{(3)}| = |U_{e3}|^2 \sqrt{\Delta m_{32}^2 + \Delta m_{21}^2 + m_1^2}. \quad (3)$$

The effective mass $\langle m \rangle$ is related with the half-life for $0\nu\beta\beta$ decay via $(T_{1/2}^{0\nu})^{-1} \sim \langle m_\nu \rangle^2$, and for the limit on $T_{1/2}^{0\nu}$ deducible in an experiment we have

$$T_{1/2}^{0\nu} \sim \epsilon \times a \sqrt{\frac{Mt}{\Delta EB}}, \quad (4)$$

Here a is the isotopical abundance of the $\beta\beta$ emitter; M is the active detector mass; t is the measuring time; ΔE is the energy resolution; B is the background count rate and ϵ is the efficiency for detecting a $\beta\beta$ signal. Determination of the effective mass fixes the absolute scale of the neutrino mass spectrum. ^{5,7}).

In this paper we will discuss the status of double beta decay search. We shall, in section 2, discuss the recent evidence for the neutrinoless decay mode, from the HEIDELBERG-MOSCOW experiment and the consequences for the neutrino mass scenarios which could be realized in nature. In section 3 we discuss the possible future potential of $0\nu\beta\beta$ experiments, which could improve the present accuracy.

2. Evidence for the Neutrinoless Decay Mode

The status of present double beta experiments is shown in Fig. 1 and is extensively discussed in ⁷. The HEIDELBERG-MOSCOW experiment using the largest source strength of 11 kg of enriched ^{76}Ge (enrichment 86%) in form of five HP Ge-detectors is running since August 1990 in the Gran-Sasso underground laboratory ^{7,3,4,1,32,28}, and is since nine years now the most sensitive double beta experiment worldwide.

2.1. Data from the HEIDELBERG-MOSCOW Experiment

The data taken in the period August 1990 - May 2000 (54.9813 kg y, or 723.44 mol-years) are shown in Fig. 2 in the section around the $Q_{\beta\beta}$ value of 2039.006 keV ^{16,17}. Fig. 2 is identical with Fig. 1 in ¹, except that we show here the original energy binning of the data of 0.36 keV. These data have been analysed ^{1,2,3} with various statistical methods, with the Maximum Likelihood Method and in particular also with the Bayesian method (see, e.g. ¹¹). This

method is particularly suited for low counting rates, where the data follow a Poisson distribution, that cannot be approximated by a Gaussian. Details and the results of the analysis are given in ^{1,2,3}.

Our peak search procedure (for details see ^{2,3}) reproduces (see ^{1,2,3}) γ -lines at the positions of known weak lines from the decay of ^{214}Bi at 2010.7, 2016.7, 2021.8 and 2052.9 keV ¹⁵. In addition, a line centered at 2039 keV shows up (see Fig. 3). This is compatible with the Q-value ^{16,17} of the double beta decay process. The Bayesian analysis yields, when analysing a $\pm 5\sigma$ range around $Q_{\beta\beta}$ (which is the usual procedure when searching for resonances in high-energy physics) a confidence level (i.e. the probability K) for a line to exist at 2039.0 keV of 96.5 % c.l. (2.1σ) (see Fig. 3). We repeated the analysis for the same data, but except detector 4, which had no muon shield and a slightly worse energy resolution (46.502 kg y). The probability we find for a line at 2039.0 keV in this case is 97.4% (2.2σ) ^{1,2,3}.

Fitting a wide range of the spectrum yields a line at 2039 keV at 91% c.l. (see Fig.2).

We also applied the Feldman-Cousins method¹². This method (which does not use the information that the line is Gaussian) finds a line at 2039 keV on a confidence level of 3.1 σ (99.8% c.l.). In addition to the line at 2039 keV

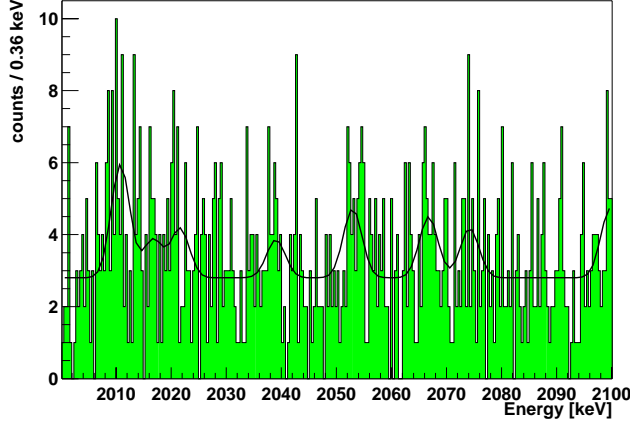


Figure 2. The spectrum taken with the ^{76}Ge detectors Nr. 1,2,3,4,5 over the period August 1990 - May 2000 (54.9813 kg y) in the original 0.36 keV binning, in the energy range 2000 - 2100 keV. Simultaneous fit of the ^{214}Bi lines and the two high-energy lines yield a probability for a line at 2039.0 keV of 91%.

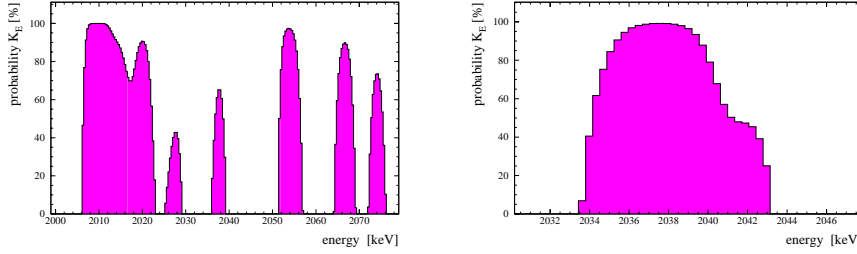


Figure 3. Left: Probability K that a line exists at a given energy in the range of 2000-2080 keV derived via Bayesian inference from the spectrum shown in Fig. 2. Right: Result of a Bayesian scan for lines as in the left part of this figure, but in an energy range of $\pm 5\sigma$ around $Q_{\beta\beta}$.

we find candidates for lines at energies beyond 2060 keV and around 2030 keV, which at present cannot be attributed. This is a task of nuclear spectroscopy.

Important further information can be obtained from the *time structures* of the individual events. Double beta events should behave as single site events (see Fig. 4 left), i.e. clearly different from a multiple scattered γ -event (see Fig. 4 right). It is possible to differentiate between these different types of events by pulse shape analysis. We have developed three methods of pulse shape analysis^{8,9,10} during the last seven years, one of which has been patented and therefore only published recently.

Installation of Pulse Shape Analysis (PSA) has been performed in 1995 for

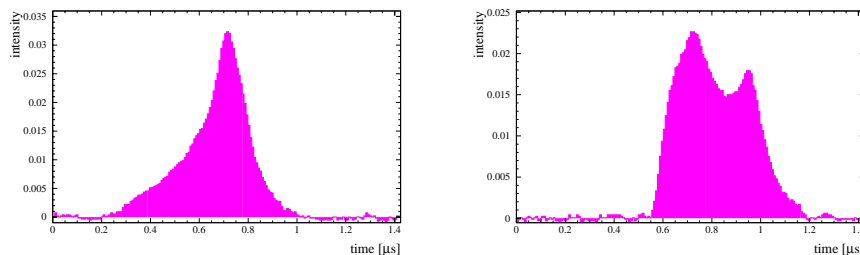


Figure 4. Left: Shape of one candidate for $0\nu\beta\beta$ decay classified as SSE by all three methods of pulse shape discrimination. Right: Shape of one candidate classified as MSE by all three methods.

the four large detectors. Detector Nr.5 runs since February 1995, detectors 2,3,4 since November 1995 with PSA. The measuring time with PSA from November 1995 until May 2000 is 36.532 kg years, for detectors 2,3,5 it is 28.053 kg y.

In the SSE spectrum obtained under the restriction that the signal simultaneously fulfills the criteria of *all three* methods for a single site event, we find again indication of a line at 2039.0 keV (see Figs. 5, 6).

We find 9 SSE events in the region 2034.1 - 2044.9 keV ($\pm 3\sigma$ around $Q_{\beta\beta}$). Bayes analysis of the range 2032 - 2046 keV yields a signal of single site events, as expected for neutrinoless double beta decay, with 96.8% c.l. at the $Q_{\beta\beta}$ value. The Feldman-Cousins method gives a signal at 2039.0 keV of 2.8σ (99.4%).

The analysis of the line at 2039.0 keV before correction for the efficiency yields 4.6 events (best value) or (0.3 - 8.0) events within 95% c.l. ((2.1 - 6.8) events within 68.3% c.l.). Corrected for the efficiency to identify an SSE signal by successive application of all three PSA methods, which is 0.55 ± 0.10 , we obtain a $0\nu\beta\beta$ signal with 92.4% c.l.. The signal is (3.6 - 12.5) events with 68.3% c.l. (best value 8.3 events). Thus, with proper normalization concerning the running times (kg y) of the full and the SSE spectra, we see that almost the full signal remains after the single site cut (best value), while the ^{214}Bi lines (best values) are considerably reduced. We have used a ^{238}Th source to test the PSA method. We find the reduction of the 2103 keV and 2614 keV ^{228}Th lines (known to be multiple site or mainly multiple site), relative to the 1592 keV ^{228}Th line (known to be single site), shown in Fig. 7. This proves that the PSA method works efficiently. Essentially the same reduction as for the Th lines at 2103 and 2614 keV and for the weak Bi lines is found for the strong ^{214}Bi lines (e.g. at 609.6 and 1763.9 keV (Fig. 7)).

The possibility, that the single site signal is the double escape line cor-

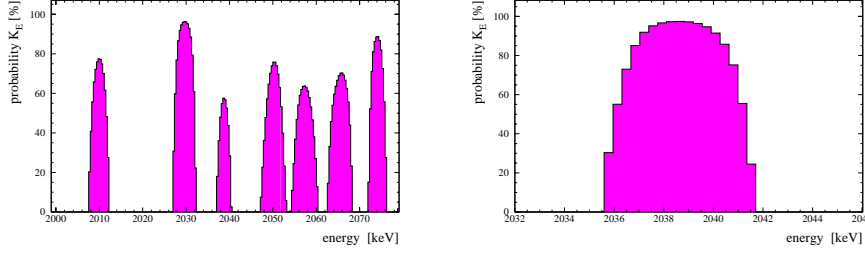


Figure 5. Scan for lines in the single site event spectrum taken from 1995-2000 with detectors Nr. 2,3,5, (Fig. 6), with the Bayesian method. Left: Energy range 2000 -2080 keV. Right: Energy range of analysis $\pm 4.4\sigma$ around $Q_{\beta\beta}$.

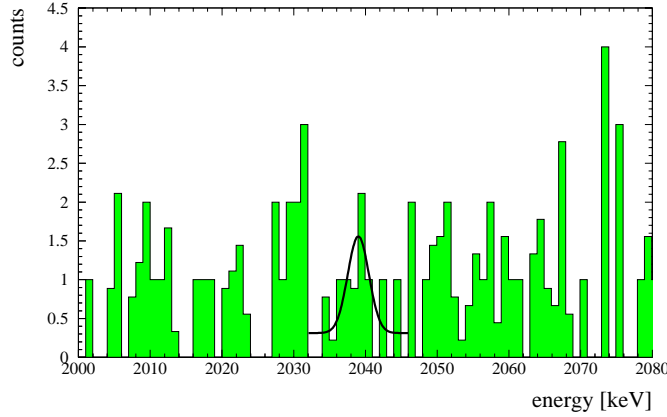


Figure 6. Sum spectrum of single site events, measured with the detectors Nr. 2,3,5 operated with pulse shape analysis in the period November 1995 to May 2000 (28.053 kg y), summed to 1 keV bins. Only events identified as single site events (SSE) by all three pulse shape analysis methods ^{8,9,10} have been accepted. The curve results from Bayesian inference in the way explained in sec.3. When corrected for the efficiency of SSE identification (see text), this leads to the following value for the half-life: $T_{1/2}^{0\nu} = (0.88 - 22.38) \times 10^{25}$ y (90% c.l.).

responding to a (much more intense!) full energy peak of a γ -line, at $2039+1022=3061$ keV is excluded from the high-energy part of our spectrum.

2.2. Comparison with earlier results

We applied the same methods of peak search as used in our analysis to the spectrum, measured in the Ge experiment by Caldwell et al. ¹⁸ more than a decade ago. These authors had the most sensitive experiment using *natural* Ge detectors (7.8% abundance of ^{76}Ge). With their background being a factor of

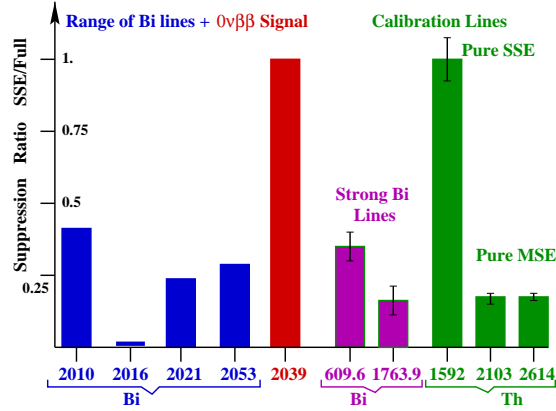


Figure 7. Relative suppression ratios: Remaining intensity after pulse shape analysis compared to the intensity in the full spectrum. Right: Result of a calibration measurement with a Th source - ratio of the intensities of the 1592 keV line (double escape peak, known to be 100% SSE), set to 1. The intensities of the 2203 keV line (single escape peak, known to be 100% MSE) are strongly reduced (error bars are $\pm 1\sigma$). The same order of reduction is found for the strong Bi lines occurring in our spectrum - shown in this figure are the lines at 609.4 and 1763.9 keV. Left: The lines in the range of weak statistics around the line at 2039 keV (shown are ratios of best fit values). The Bi lines are reduced compared to the line at 2039 keV (set to 1), as to the 1592 keV SSE Th line.

9 higher than in the present experiment, and their measuring time of 22.6 kg y, they have a statistics for the background larger by a factor of almost 4 in their (very similar) experiment. This allows helpful conclusions about the nature of the background.

The peak scanning finds ³ (Fig. 8) indications for peaks essentially at the same energies as in Fig. 3. This shows that these peaks are not fluctuations. In particular it sees the 2010.78, 2016.7, 2021.6 and 2052.94 keV ^{214}Bi lines. It finds, however, *no line at $Q_{\beta\beta}$* . This is consistent with the expectation from the rate found from the HEIDELBERG-MOSCOW experiment. About 16 observed events in the latter correspond to 0.6 *expected* events in the Caldwell experiment, because of the use of non-enriched material and the shorter measuring time.

Another Ge experiment (IGEX) using 8.8 kg of enriched ^{76}Ge , but collecting since beginning of the experiment in the early nineties till shutdown in end of 1999 only 8.8 kg y of statistics ⁴², because of this low statistics also naturally cannot see any signal at 2039 keV. This is consistent with our result. The number of counts expected in that experiment from our result would be about only 2.6. In their spectrum however, which is unfortunately shown only in the energy range 2020-2060 keV, the line around 2030 keV, indicated in Figs. 3,6, is also clearly seen.

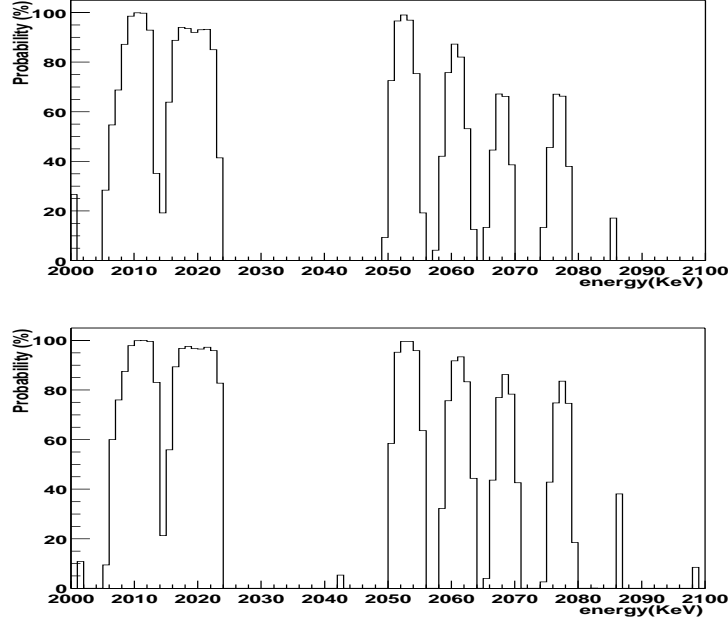


Figure 8. Peak scanning of the spectrum measured by Caldwell et al.¹⁸, with the Maximum Likelihood method (upper part), and with the Bayesian method (lower part) (as in Figs. 3,6) (see³).

2.3. Proofs and Disproofs

The result described in section 2.1 has been questioned in some papers (Aalseth et al, hep-ex/0202018; Feruglio et al., Nucl. Phys. B 637(2002)345; Zdesenko et al., Phys. Lett. B 546(2002) 206, and Kirpichnikov, talk at Meeting of Physical Section of Russian Academy of Sciences, Moscow, December 2, 2002, and priv. communication, Dec. 3, 2002.) These claims against our results are incorrect in various ways.

The arguments in the first two of these papers can be easily rejected. We have published this in hep-ph/0205228. In particular their estimates of the intensities of the ^{214}Bi lines are simply wrong, because the summing effect of the energies of consecutive gamma lines (more precisely called True Coincidence Summing - TCS) which is an elementary effect known in nuclear spectroscopy, was not taken into account (for a detailed discussion see³). Further none of the papers has performed a Monte Carlo simulation of our setup, which is the only way to come to quantitative statements.

The paper by Zdesenko et al. starts from an arbitrary assumption, namely that there are lines in the spectrum *at best* only at 2010 and 2053 keV. This contradicts to the experimental result, according to which there are further

lines in the spectrum (see Figs. 3,5,8 in the present paper). In this way they artificially increase the background in their analysis and come to wrong conclusions.

All three of these papers, when discussing the choice of the width of the search window, ignore the results of the statistical simulations we give in hep-ph/0205228 and we have published in ² and ³.

Kirpichnikov states that from his analysis he clearly sees the 2039 keV line in the full (not pulse shape discriminated) spectrum with $> 99\%$ c.l. He claims that he does not see the signal in the pulse shape spectrum. One reason to see less intensity certainly is that in this case he averages for determination of the background over the full energy range without allowing for any lines. His result is in contradiction with the result we obtain under the same assumption of assuming just one line (at $Q_{\beta\beta}$) and a continuous background (see Fig. 5 of this paper).

2.4. Half-Life and Effective Neutrino Mass

Having shown that the signal at $Q_{\beta\beta}$ consists of single site events and is not a γ -line, we translate the observed number of events into half-lives. We obtain ^{1,2,3} $T_{1/2}^{0\nu} = (0.8 - 18.3) \times 10^{25}$ y (95% c.l.) with a best value of 1.5×10^{25} y. Assuming that the $0\nu\beta\beta$ amplitude is dominated by the neutrino mass mechanism, we obtain, with the nuclear matrix element from ¹³ an effective mass of $\langle m_\nu \rangle = (0.11 - 0.56)$ eV (95% c.l.).

The result obtained is consistent with all other double beta experiments - which still reach less sensitivity. The most sensitive experiments following the HEIDELBERG-MOSCOW experiment are the geochemical ¹²⁸Te experiment with $T_{1/2}^{0\nu} > 2(7.7) \times 10^{24}$ y (68% c.l.), ²⁰ the ¹³⁶Xe experiment by the DAMA group with $T_{1/2}^{0\nu} > 1.2 \times 10^{24}$ y (90% c.l.)²¹, a second ⁷⁶Ge experiment with $T_{1/2}^{0\nu} > 1.2 \times 10^{24}$ y ¹⁹ and a ^{nat}Ge experiment with $T_{1/2}^{0\nu} > 1 \times 10^{24}$ y ^{18,19}. Other experiments are already about a factor of 100 less sensitive concerning the $0\nu\beta\beta$ half-life: the Gotthard TPC experiment with ¹³⁶Xe yields ²² $T_{1/2}^{0\nu} > 4.4 \times 10^{23}$ y (90% c.l.) and the Milano Mibeta cryodetector experiment ⁴⁴ $T_{1/2}^{0\nu} > 1.44 \times 10^{23}$ y (90% c.l.).

Another experiment ⁴² with enriched ⁷⁶Ge, which has stopped operation in 1999 after reaching a significance of 8.8 kg y, yields (if one believes their method of 'visual inspection' in their data analysis), in a conservative analysis, a limit of about $T_{1/2}^{0\nu} > 5 \times 10^{24}$ y (90% c.l.). The ¹²⁸Te geochemical experiment yields $\langle m_\nu \rangle < 1.1$ eV (68 % c.l.) ²⁰, the DAMA ¹³⁶Xe experiment $\langle m_\nu \rangle < (1.1 - 2.9)$ eV ²¹ and the ¹³⁰Te cryogenic experiment yields $\langle m_\nu \rangle < 1.8$ eV ⁴⁴.

Concluding we obtain, with about 95% probability, first evidence for the

neutrinoless double beta decay mode. As a consequence, at this confidence level, lepton number is not conserved. Further the neutrino is a Majorana particle. If the $0\nu\beta\beta$ amplitude is dominated by exchange of a massive neutrino the effective mass $\langle m \rangle$ is deduced to be $\langle m \rangle = (0.11 - 0.56) \text{ eV}$ (95% c.l.), with best value of 0.39 eV. Allowing conservatively for an uncertainty of the nuclear matrix elements of $\pm 50\%$ (for detailed discussions of the status of nuclear matrix elements we refer to ^{7,3,14} and references therein) this range may widen to $\langle m \rangle = (0.05 - 0.84) \text{ eV}$ (95% c.l.).

Assuming other mechanisms to dominate the $0\nu\beta\beta$ decay amplitude, the result allows to set stringent limits on parameters of SUSY models, lept-quarks, compositeness, masses of heavy neutrinos, the right-handed W boson and possible violation of Lorentz invariance and equivalence principle in the neutrino sector. For a discussion and for references we refer to ^{7,23,26,34,46}.

With the limit deduced for the effective neutrino mass, the HEIDELBERG-MOSCOW experiment excludes several of the neutrino mass scenarios allowed from present neutrino oscillation experiments - allowing only for degenerate and inverse hierarchy mass scenarios ⁶.

Assuming the degenerate scenarios to be realized in nature we fix - according to the formulae derived in ⁵ - the common mass eigenvalue of the degenerate neutrinos to $m = (0.05 - 3.4) \text{ eV}$. Part of the upper range is already excluded by tritium experiments, which give a limit of $m < 2.2\text{-}2.8 \text{ eV}$ (95% c.l.) ³⁰. The full range can only partly (down to $\sim 0.5 \text{ eV}$) be checked by future tritium decay experiments, but could be checked by some future $\beta\beta$ experiments (see, e.g., next section). The deduced best value for the mass is consistent with expectations from experimental $\mu \rightarrow e\gamma$ branching limits in models assuming the generating mechanism for the neutrino mass to be also responsible for the recent indication for an anomalous magnetic moment of the muon ⁵⁰. It lies in a range of interest also for Z-burst models recently discussed as explanation for super-high energy cosmic ray events beyond the GKZ-cut-off ^{48,49,52}. A recent model with underlying A_4 symmetry for the neutrino mixing matrix also leads to degenerate neutrino masses consistent with the present result from $0\nu\beta\beta$ decay ⁵¹. The range of $\langle m \rangle$ fixed in this work is, already now, in the range to be explored by the satellite experiments MAP and PLANCK ^{27,5} (see Fig. 10).

The neutrino mass deduced leads to $0.002 \geq \Omega_\nu h^2 \leq 0.1$ and thus may allow neutrinos to still play an important role as hot dark matter in the Universe ³³.

3. Future of $\beta\beta$ Experiments - GENIUS and Other Proposals

With the HEIDELBERG-MOSCOW experiment, the era of the small smart experiments is over. New approaches and considerably enlarged experiments

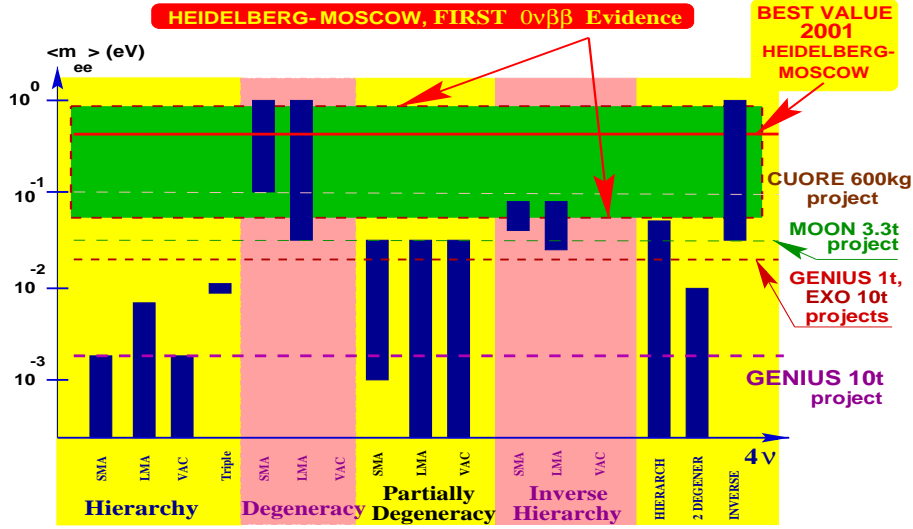


Figure 9. The impact of the evidence obtained for neutrinoless double beta decay in this paper (best value of the effective neutrino mass $\langle m \rangle = 0.39 \text{ eV}$, 95% confidence range $(0.05 - 0.84) \text{ eV}$ - allowing already for an uncertainty of the nuclear matrix element of a factor of $\pm 50\%$) on possible neutrino mass schemes. The bars denote allowed ranges of $\langle m \rangle$ in different neutrino mass scenarios, still allowed by neutrino oscillation experiments (see ⁶). Hierarchical models are excluded by the new $0\nu\beta\beta$ decay result. Also shown are the expected sensitivities for the future potential double beta experiments CUORE, MOON, EXO and the 1 ton and 10 ton project of GENIUS ^{7,34,47,25}.

(as discussed, e.g. in ^{7,26,47,25,29}) will be required in future to fix the neutrino mass with higher accuracy.

Since it was realized in the HEIDELBERG-MOSCOW experiment, that the remaining small background is coming from the material close to the detector (holder, copper cap, ...), elimination of *any* material close to the detector will be decisive. Experiments which do not take this into account, like, e.g. CUORE ⁴³, and MAJORANA ⁴⁵, will allow at best only rather limited steps in sensitivity. Furthermore there is the problem in cryodetectors that they cannot differentiate between a β and a γ signal, as this is possible in Ge experiments.

Another crucial point is - see eq. (4) - the energy resolution, which can be optimized *only* in experiments using Germanium detectors or bolometers. It will be difficult to probe evidence for this rare decay mode in experiments, which have to work - as result of their limited resolution - with energy windows around $Q_{\beta\beta}$ of several hundreds of keV, such as NEMO III⁴¹, EXO³⁹, CAMEO⁴⁰.

Another important point is (see eq. 4), the efficiency of a detector for detec-

m_1 (eV) **HEIDELBERG-MOSCOW Positive EVIDENCE**

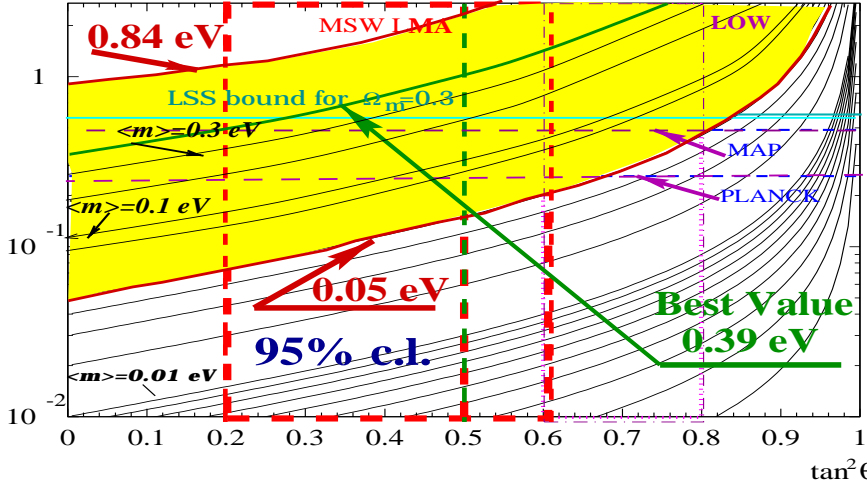


Figure 10. Double beta decay observable $\langle m \rangle$ and oscillation parameters: The case for degenerate neutrinos. Plotted on the axes are the overall scale of neutrino masses m_0 and mixing $\tan^2 \theta_{12}$. Also shown is a cosmological bound deduced from a fit of CMB and large scale structure²⁷ and the expected sensitivity of the satellite experiments MAP and PLANCK. The present limit from tritium β decay of 2.2 eV³⁰ would lie near the top of the figure. The range of $\langle m \rangle$ fixed by the HEIDELBERG-MOSCOW experiment¹ is, in the case of small solar neutrino mixing, already in the range to be explored by MAP and PLANCK²⁷.

tion of a $\beta\beta$ signal. For example, with 14% efficiency a potential future 100 kg ^{82}Se NEMO experiment would be, because of its low efficiency, equivalent only to a 10 kg experiment (not talking about the energy resolution).

In the first proposal for a third generation double beta experiment, the GENIUS proposal^{23,24,26,47,25}, the idea is to use 'naked' Germanium detectors in a huge tank of liquid nitrogen. It seems to be at present the *only* proposal, which can fulfill *both* requirements mentioned above - to increase the detector mass and simultaneously reduce the background drastically. GENIUS would - with only 100 kg of enriched ^{76}Ge - increase the confidence level of the present pulse shape discriminated $0\nu\beta\beta$ signal to 4σ within one year, and to 7σ within three years of measurement (a confirmation on a 4σ level by the MAJORANA project would at least need ~ 230 years, the CUORE project would need (ignoring for the moment the problem of identification of the signal as a $\beta\beta$ signal) 3700 years). With ten tons of enriched ^{76}Ge GENIUS should be capable to investigate also whether the neutrino mass mechanism or another mechanism (see, e.g.⁷) is dominating the $0\nu\beta\beta$ decay amplitude. A

GENIUS Test Facility is at present under construction in the GRAN SASSO Underground Laboratory^{37,36}.

4. Conclusion

The status of present double beta decay search has been discussed, and recent evidence for a non-vanishing Majorana neutrino mass obtained by the HEIDELBERG-MOSCOW experiment has been presented. Future projects to improve the present accuracy of the effective neutrino mass have been briefly discussed. The most sensitive of them and perhaps at the same time most realistic one, is the GENIUS project. GENIUS is the only of the new projects which simultaneously has a huge potential for cold dark matter search, and for real-time detection of low-energy neutrinos (see^{23,29,31,34,38,35,46}).

5. Acknowledgment

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